Updating a Land Surface Model with MODIS-Derived Snow Cover

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ABSTRACT

A simple scheme for updating snow-water storage in a land surface model using snow cover observations is presented. The scheme makes use of snow cover observations retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's *Terra* and *Aqua* satellites. Simulated snow-water equivalent is adjusted when and where the model and MODIS observation differ, following an internal accounting of the observation quality, by either removing the simulated snow or adding a thin layer. The scheme is tested in a 101-day global simulation of the Mosaic land surface model driven by the NASA/NOAA Global Land Data Assimilation System. Output from this simulation is compared to that from a control (not updated) simulation, and both are assessed using a conventional snow cover product and data from ground-based observation networks over the continental United States. In general, output from the updated simulation displays more accurate snow coverage and compares more favorably with in situ snow time series. Both the control and updated simulations have serious deficiencies on occasion and in certain areas when and where the precipitation and/or surface air temperature forcing inputs are unrealistic, particularly in mountainous regions. Suggestions for developing a more sophisticated updating scheme are presented.

1. Introduction

In middle- to high-latitude and alpine regions, the seasonal snowpack can dominate the surface energy and water budgets because of its high albedo, substantial heat capacity and insulating properties, and ability to store and then quickly release a winter's worth of precipitation. Furthermore, scientists have recently identified teleconnections between the snowpack in certain regions and subsequent meteorological conditions in other regions. Bamzai and Shukla (1999) used satellite- and ground-based observations to confirm a previously inferred inverse relationship between winter snow cover over western Eurasia and subsequent Indian summer monsoon rainfall. Several observation-based studies have shown that Eurasian snow cover influences the state and persistence of the Arctic Oscillation (Cohen and Entekhabi 1999, 2001; Bojariu and Gimeno 2003; Saito and Cohen 2003; Saunders et al. 2003), which in turn affects the severity of the winter season in the entire Northern Hemisphere. Similarly, Gong et al. (2002, 2003) used atmospheric models to demonstrate that Siberian snow perturbations modulate the Arctic Oscillation. Thus the accurate representation of snow cover is crucial to numerical weather prediction models for producing reliable daily to seasonal forecasts, yet these models often have difficulty simulating snow cover and water storage during times of accumulation and ablation (Foster et al. 1996). Dependable snow data are also critical for flood preparedness and water management applications as well as for developing a comprehensive understanding of the global hydrological cycle.

The Moderate Resolution Imaging Spectroradiometer (MODIS) instruments (Justice et al. 1998) on the National Aeronautics and Space Administration's (NASA's) *Terra* and *Aqua* satellites are now providing high-resolution daily observations of snow cover. However, this snow cover information simply stipulates the presence or absence of snow, as opposed to snow-water equivalent (or depth) information, which actually quantifies the snowpack. The latter is more desirable for most applications and water budget studies. Furthermore, MODIS can neither ''see'' through clouds nor make observations at night. Therefore MODIS observations alone are unsatisfactory for forecasting applications.

Incorporating satellite-based snow observations into sophisticated land surface models (LSMs), which provide spatial and temporal continuity and also quantify the snowpack, may be the key to producing accurate, high-resolution maps of snow-water equivalent in near–real time. LSMs provide spatial and temporal continuity and also quantify the snow water storage, but the quality of their output is limited by the quality of the input forcing data and the simplifications necessary to simulate complex physical processes economically. This is the premise behind data assimilation. The following sections describe

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the development and testing of a simple algorithm for updating a global, high-resolution land surface model with snow cover data derived from MODIS observations. The goal is to improve the simulation of snow in an LSM despite the shortcomings of the model's snow formulation and the atmospheric forcing data.

5. Discussion

The updating scheme presented here was developed in order to exploit the snow cover information contained in MODIS data, despite its limitations. In particular, MODIS cannot resolve snow-depth or -water equivalent, nor can it ''see'' through clouds. However, MODIS may have certain advantages over the Advanced Microwave Scanning Radiometer (AMSR) aboard NASA's *Aqua* satellite, which can be used to estimate snow-water equivalent. First, MODIS is deployed on both *Terra* (launched 18 December 1999) and *Aqua* (launched 4 May 2002), so that the MODIS data have greater coverage and a longer record. Second, the retrieval of snow-water equivalent from AMSR data is complicated by many factors including vegetation, liquid water in the snowpack, and electromagnetic interference. Therefore it is worthwhile to develop techniques to utilize both types of observations with the ultimate goal of producing a single model-assimilated product.

TABLE 2. Statistics of comparison of regional-average time series of modeled, assimilated, and observed snow-water equivalent. Relative bias was calculated as the mean bias over the mean observed snow water equivalent over the time period.

Region and simulation	Rms error (mm)	Mean bias (mm)	Relative bias (%)	Correlation coefficient
Eastern Montana control	30.5	26.2	350	0.11
Eastern Montana updated	6.3	3.2	43	0.58
Midwest control	3.1	2.2	106	0.63
Midwest updated	1.4	0.0	0	0.83
Mid-Atlantic control	15.0	13.9	320	0.75
Mid-Atlantic updated	8.0	5.5	126	0.81

The results demonstrate that the updating scheme skillfully removes superfluous modeled snow, but that it results in an increase in snow much less frequently. This may be due in part to the fact that the updates began on 1 January, well after the start of northern winter. If updates had begun in the previous autumn, snow added to some areas might have provided a base to allow subsequent snowfall to accumulate, and the increased (relative to the control) snow amounts might have persisted through to the spring. Ineffectiveness of the scheme in adding snow is also attributed to the thinness of the added snow layer, 5-mm water equivalent, which melts away quickly if the forcing near surface air temperature is much above freezing. Adding even a thin layer of snow can have important consequences for the simulated energy balance because snow has a high albedo. However, in the case of Mosaic, 5 mm is the minimum amount of snow that can modify albedo, so that any melting eliminates that effect. The thickness of the added layer can easily be increased in this updating scheme, but the difficulty in adding snow might also be handled more cleverly, as described below.

Data assimilation may have deleterious effects on other water and/or energy processes when the data assimilation fluxes are large. This is one reason for adding only a thin layer of snow. The data assimilation fluxes can be especially detrimental if snow is added and immediately melts day after day, in a location where MODIS identifies snow but the model prevents snow from remaining. For example, snow was added to the model grid cell containing Baldy Peak in west-central Arizona 45 times during the 101-day simulation, which would have been equivalent to a more than 20-cm increase in precipitation. The explanation is that Baldy Peak is not resolved at the resolution of the GEOS input ($1° \times 1.25°$), so that the forcing air temperature, which is an average meant to represent Baldy Peak and the surrounding area of Arizona, is too high to sustain snow. Snow was added to individual grid cells (at least one subgrid tile) 108 184 times during the 101-day simulation, and on 21 700 of those occasions snow was added to the same grid cell again the following day. From these numbers and with several implicit assumptions, it is estimated that snow added by the updating scheme is melted by the model immediately and erroneously about 20% of the time.

A more sophisticated updating scheme should attempt to minimize these assimilation fluxes. One approach would be to develop a multivariate snow assimilation scheme, thus incorporating observations of snow-water equivalent (as from AMSR) as well as other land surface states whose bias adversely interacts with the snow states (i.e., surface temperature). However, a surface temperature constraint would have to be applied continuously because soil temperature has little inertia. Tests (not presented here) showed that simply adjusting the surface temperature to freezing whenever snow was added did not influence the persistence of snow cover appreciably. Adjusting the near-surface air temperature forcing might be more effective. Another potential solution is to couple an atmospheric boundary layer model to the land surface model to enable feedbacks between the updated snow state and the atmosphere, possibly resolving the air temperature–related problems. It is also recommended that future updating schemes take advantage of the high resolution of MODIS observations. This could be accomplished by variably adjusting the snow-water equivalent based on the percentage of snow cover in the MODIS observation, or by updating the model's representation of subgrid snow coverage, if it exists. Finally, a snow-impossible mask that varies with time would also improve the results.